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Linking modelling and experimentation to better capture crop impacts of agroclimatic extremes—A review

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ABSTRACT

Climate change implies higher frequency and magnitude of agroclimatic extremes threatening plant production and the provision of other ecosystem services. This review is motivated by a mismatch between advances made regarding deeper understanding of abiotic stress physiology and its incorporation into ecophysiological models in order to more accurately quantifying the impacts of extreme events at crop system or higher aggregation levels.

Adverse agroclimatic extremes considered most detrimental to crop production include drought, heat, heavy rains/hail and storm, flooding and frost, and, in particular, combinations of them.

Our core question is: How have and could empirical data be exploited to improve the capability of widely used crop simulation models in assessing crop impacts of key agroclimatic extremes for the globally most important grain crops? To date there is no comprehensive review synthesizing available knowledge for a broad range of extremes, grain crops and crop models as a basis for identifying research gaps and prospects.

To address these issues, we selected eight major grain crops and performed three systematic reviews using SCOPUS for period 1995–2016. Furthermore, we amended/complemented the reviews manually and performed an in-depth analysis using a sub-sample of papers.

Results show that by far the majority of empirical studies (1631 out of 1772) concentrate on the three agroclimatic extremes drought, heat and heavy rain and on the three major staples wheat, maize and rice (1259 out of 1772); the concentration on just a few has increased over time. With respect to modelling studies two model families, i.e. CERES-DSSAT and APSIM, are clearly dominating for wheat and maize; for rice, ORYZA2000 and CERES-Rice predominate and are equally strong. For crops other than maize and wheat the number of studies is small. Empirical and modelling papers don't differ much in the proportions the various extreme events are dealt with – drought and heat stress together account for approx. 80% of the studies. There has been a dramatic increase in the number of papers, especially after 2010.

As a way forward, we suggest to have very targeted and well-designed experiments on the specific crop impacts of a given extreme as well as of combinations of them. This in particular refers to extremes addressed with insufficient specificity (e.g. drought) or being under-researched in relation to their economic importance (heavy rains/storm and flooding). Furthermore, we strongly recommend extending research to crops other than wheat, maize and rice.

1. Introduction

1.1. Background and objectives

Sustainably increasing crop production to meet the projected increase in food demand of > 60% by 2050 compared to present (Alexandratos and Bruinsma 2012), in the face of climatic change, is a major challenge of the 21 st century (Godfray et al., 2010; Wheeler and von Braun, 2013). Increased occurrence and magnitude of adverse and extreme agroclimatic events are considered a major threat to global food security (Lobell and Gourdji, 2012; Trnka et al., 2014; Chenu et al., 2017).

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Some authors have estimated that the annual costs of adaptation in the agriculture, forestry and fishery sectors will amount to at least US$ 14 billion annually by 2030 to cope with the adverse impacts of climate change – though that figure could be two to three times greater (see, Fankhauser, 2010).

Extreme weather is usually defined as the extremes of temperature, precipitation, winds and other phenomena of their historical distribution—i.e. the range that has been seen in the past (Field et al., 2012). Hence, "an extreme event can be typified by its physical intensity, duration or frequency of occurrence." (Rummukainen, 2012;). For this paper, we focus on such adverse and extreme agroclimatic events that are considered most detrimental to crop production – including drought, heat, heavy rains/storm, flooding and frost, or a combination of them (Cattivelli et al., 2008; Battisti and Naylor, 2009; Schlenker and Roberts, 2009; Hakala et al., 2012; Trnka et al., 2011, 2014). This specification implies that we also consider sequences of weather and climate events which are not necessarily extreme by themselves but bring about extreme (cumulative) effects (Hegerl et al., 2011; Rummukainen, 2012)., such as a number of dry spells over the growing season leading to substantial water deficits and substantial yield loss or flooding which may occur as on-side effect of heavy rain happening somewhere else.

Climate change implies higher frequency of extreme weather events (Coumou et al., 2015; IPCC, 2013; Field et al., 2014; Mann et al., 2017) such as heat waves (e.g. Christidis et al., 2015), drought (Dai, 2013; Sheffield and Wood, 2008; Schauberger et al., 2017) or hail (Brimelow et al., 2017) – to name a few – causing reduced crop yields and plant production and threatening the provision of other ecosystem services (Field et al., 2012; Powell and Reinhard, 2016; Rummukainen, 2014).

Whether in tropical or temperate regions, we are already observing more frequent and severe extreme weather events (Alexander et al., 2006; Coumou and Rahmstorf, 2012; Hakala et al., 2012; Lobell et al., 2011; Rummukainen, 2012; Tebaldi et al., 2006 Trenberth et al., 2015; Zheng et al., 2012), in particular increased droughts (Lesk et al., 2016); heat waves (Gourdji et al., 2013) and heavy rainfall events (Lehmann et al., 2015) that affect many important agricultural areas.

The overall picture emerging from the literature on shifts in extremes under a changing climate – summarized by Rummukainen (2012, p116) on the basis of the SREX (Field et al., 2012), as well as the AR4 and AR5 of the Intergovernmental Panel on Climate Change (Field et al., 2014) looks as follows:

- Increased frequency, intensity and duration of heat waves/extreme high temperature events, exceeding the changes in the mean temperature
- Increased heavy precipitation, exceeding the changes in the mean
- Increased drought in (many) different parts of the world
- Decreased cold extremes, exceeding the changes in the mean temperature

For assessing climate change impacts and *ex- ante* evaluation of a multitude of adaptation options, fairly complex and well-tested modelling tools are required, which go beyond empirical descriptions (Rötter et al., 2013a; Tao et al., 2017; Ruiz-Ramos et al., 2018). Process-based crop growth simulation models have proven to be the best available tools for this purpose, as they are capable of exploring genotype × environment × management interactions making them key tools for understanding the processes of the complex interconnections in cropping systems (Chenu et al., 2017; Glotter and Elliot, 2017; Hoffmann et al., 2018; Rötter et al., 2015; Schauberger et al., 2017).

This review paper is motivated by recognizing that though understanding of plant stress physiology has substantially advanced and some deficiencies in crop modelling approaches have been reduced (Cattivelli et al., 2008; Ewert et al., 2015; Lobell and Asseng, 2017; Maiorano et al., 2017; Rezaei et al., 2015; Rötter et al., 2011; Siebert et al., 2017a,b; Yin et al., 2017), the majority of crop models still do not capture the impacts of most relevant extremes for the major grain crops. On the one hand, not all the available knowledge has been incorporated to improve process descriptions in the crop models (Barlow et al., 2015; Rezaei et al., 2015); on the other hand, knowledge gaps with respect to the mechanisms leading to impacts by some extremes exist (see, e.g. Pagani et al., 2017; Moshelion et al., 2014). As a result, the impacts of specific weather extremes on crop performance might often not be quantified adequately at the crop system or higher aggregation levels (Barlow et al., 2015; Rötter et al., 2015; Wang et al., 2017a).

The core question addressed in this review is: How can empirical data be exploited to improve the capability of widely used crop simulation models in assessing impacts of key agroclimatic extremes for the globally most important cereal and legume crops? A related question is, how could they be utilized for future model improvements?

To explore this, we formulated three specific objectives: (i) to examine what relevant empirical data have been utilized to increase quantitative understanding of crop impacts of specific weather extremes, (ii) to inventory available modelling studies and approaches for assessing the impacts of extremes, and (iii) to identify studies demonstrating model improvements, specify datasets required and prioritize future research.

1.2. Brief literature review

Several reviews on the physiological mechanisms causing yield penalties by extremes have been conducted, usually for one or more major crops and for one or two extremes only – among others, by Barlow et al. (2015) on heat and frost for wheat, Rezaei et al. (2015) on heat for wheat, maize and rice, Bodner et al. (2015) on drought for several cereals and grain legumes, and Gardiner et al. (2016) for wind impacts on crop growth.

A common goal of the reviews by Barlow et al. (2015) and Rezaei et al. (2015) has been to draw conclusions for guiding future crop model improvements. A few of their main points are summarized here:

- for wheat, a heat shock module is proposed that specifically accounts for the reduction in grain number around anthesis (Barlow et al., 2015), while also describing advanced senescence and reduced duration of grain filling from cumulative heat load; it is suggested to follow the procedure of the crop models GLAM (Challinor et al., 2005) and MONICA (Nendel et al., 2011) which describe the percentage reduction in grain number as a function of temperature around anthesis.
- Barlow et al. (2015) proposed a frost shock module for wheat that follows a similar approach as the proposed heat shock module and also resembles much of the frost stress index calculations by STICS (see, Brisson et al., 2003, 2008).
- Rezaei et al. (2015) suggested to study in more detail the impact of short episodes of extreme heat around flowering – which have been reported to have likely large negative effects on cereal grain yields (see, Porter and Gawith 1999 for wheat); that phenomenon had already been studied in some detail for rice in the 1970s – and empirical data had been used to modify temperature response functions to account for spikelet sterility in rice from short episodes of extreme heat (see, e.g. Horie et al., 1995); however, Jagadish et al. (2011) observed different responses under combined heat and drought stress conditions compared to independent exposure of both.
- It has also been suggested to more closely consider the combined effects of different abiotic stresses, such as heat and drought (see, e.g. Barnabas et al., 2008; Trnka et al., 2014). Combined effects cannot be explained or directly extrapolated from plant response to individual stresses (e.g. Mittler, 2006; Hlavacova et al., 2017; Hlaváčová et al., 2018; Urban et al., 2018).
- Rezaei et al. (2015) proposed consideration of canopy temperature as a driver of crop models (instead of just air temperature, as is usually done) as a promising innovation for simultaneously accounting for heat and drought (see, Webber et al., 2017).

Table 1
Selection of the eight major grain crops.

Crop		World Production[a] (1000 t)	Seed Composition[b]		
			Carbo-hydrate (g kg $^{-1}$)	Oil (g kg $^{-1}$)	Protein (g kg $^{-1}$)
Poaceae					
Maize	*Zea mays* L.	953035	800	50	100
Rice	*Oryza sativa* L.	733803	880	20	80
Wheat	*Triticum* spp.	702552	750	20	120
Barley	*Hordeum vulgare* L.	138197	760	30	120
Sorghum	*Sorghum bicolor* (L.) Moench	61110	820	40	120
Millet	*Panicum miliaceum* l.	27024	690	50	110
Fabaceae					
Soybean	*Glycine max* (L.) Merril	271888	260	170	370
Groundnut	*Arachis hypogeae* L.	42980	120	480	310

[a] Average of period 2011–2014 (FAOSTAT, 2017).
[b] As summarized by Egli (2017).

2. Materials and methods

Based on FAOSTAT (2017), we selected eight major grain crops – the six most important from the family *Poaceae*, which are maize (*Zea mays*, L.), rice (*Oryza sativa*, L.), wheat (*Triticum aestivum*, L.), barley (*Hordeum vulgare*, L.), sorghum (*Sorghum bicolor,* L. Moench) and pearl millet (*Pennisetum miliaceum*, L.) and the two most important from the family *Fabaceae*, soybean (*Glycine max*, L. Merril) and groundnut (*Arachis hypogaea*, L.) (see, Table 1).

We performed several systematic reviews on these, using the SCOPUS database (http://www.scopus.com) for the period 1995–2016. In addition, we complemented the systematic reviews by papers known and found relevant by the co-authors but not captured by the systematic searches. Similarly to related studies (e.g. White et al., 2011; Knox et al., 2016), we further carried out a manual in-depth analysis of a sub-sample of papers. A flow-chart of the review process is shown in Fig. 1.

The first overview search conducted in SCOPUS aimed at identifying most widely applied crop models. Entering the crop modelling search string (*cf.* Table S1) yielded nearly 5000 papers. We utilized three recent studies with very large ensembles of process-based crop models on wheat (Asseng et al., 2013), maize (Bassu et al., 2014), and rice (Li et al., 2015) to identify the pool of crop models from which to draw the leading and most widely applied ones dealing with the selected eight major grain crops. Using the papers with large model ensembles helped to narrow down and streamline the search.

Within the results of this search, the names of all 34 crop simulation models cited in the three above mentioned papers were queried and their frequency of citation was recorded with the aim to further concentrate on the ten most cited crop models. Infocrop and DNDC were not included as we found less than three studies in our combined literature review for crop modelling and experimentation. We therefore considered them as not fitting into the thematic scope of this review.

In order to quantify how much research has been done on the impacts of weather extremes on the selected crops during past 20 years, three systematic searches were conducted within SCOPUS. Only peer-reviewed articles and reviews published between 1995 and 2016 were considered. Further, we limited our search to papers written in German, French, English or Spanish, and to those related to subject areas "Agricultural and Biological Sciences", "Environmental Science" and "Earth and Planetary Sciences".

The aims and details of the three systematic reviews are described in detail in the Supplement (Box 1).

Some limitations of the various searches performed were the multiple listing of papers when more than one extreme, model or crop was mentioned in their title, abstract or keyword and the occasional listing of papers not meeting the search criteria (e.g. published before 1995; or dealing with other crops than the eight selected ones).

3. Results

3.1. Systematic review of empirical studies on effects of specific weather extremes on major grain crops

The first systematic search aimed at empirical studies examining the effects of key weather extremes on eight major crops and resulted in 3641 papers. When looking at these papers covering the period 1995–2016 (Table 2 and Fig. 2i) and breaking down this list of publications for each crop individually – covering each of the eight specific crops in combination with a particular extreme (Fig. 2a–h) – it was obvious that papers on drought effects are clearly dominating, with heat following some distance behind; with the exception of groundnut and millet, where heavy rain replaced heat as the second important extreme (see, also Fig. S2).

The predominance of papers dealing with drought has even been increasing after around year 2005; for papers dealing with heat, a marked increase happened since 2010, in particular for those dealing with wheat, maize and rice – and to a lesser extent, for barley, sorghum and soybean. Overall, for the 22 years' period (1995–2016) we found more than 1101 papers on drought, nearly 339 on heat, but far less for the other extremes (in the order of 100–200) (see, Fig. S2).

When we examined the number of papers from the perspective of the combination of major grain crop with individual extreme events (as shown in Fig. S1), not surprisingly, we found for drought that most papers deal with the three main staples, wheat, maize and rice. Thereafter follow, in relatively small numbers, papers on the other major grain crops. Striking was the fact that the proportion of papers dealing with the three major staple crops has become distinctly larger over time – with an acceleration after 2005. For heat, there was a clearly smaller number of papers than for drought; yet, the marked increase in papers, especially for wheat and maize was also obvious (after year 2007). The number of papers on other extremes remained limited (see, also Fig. S2).

We also examined shifts in the proportion of papers for the various grain crops by comparing the percentages for each at the three start years (1995–97) (n = 104) and end years (i.e. 2014–16) (n = 409) of the review period (Fig. S3). There were no major shifts, but compared to the sample of papers at the start, there was a relatively higher share of papers on maize and rice observed at the end of the period – and a decline of papers on groundnut and millet.

The proportion of papers with observed impacts of extremes for the individual crops (Fig. S4a) revealed that the three staples, wheat (32%), maize (22%) and rice (18%) together almost cover nearly three quarters of all papers. Next in line were soybean, barley, and sorghum with, 9%, 7% and 6%, respectively.

A comparison of the number of papers per crop with simulated impacts of extremes (Fig. S4b) revealed a clearly stronger dominance of

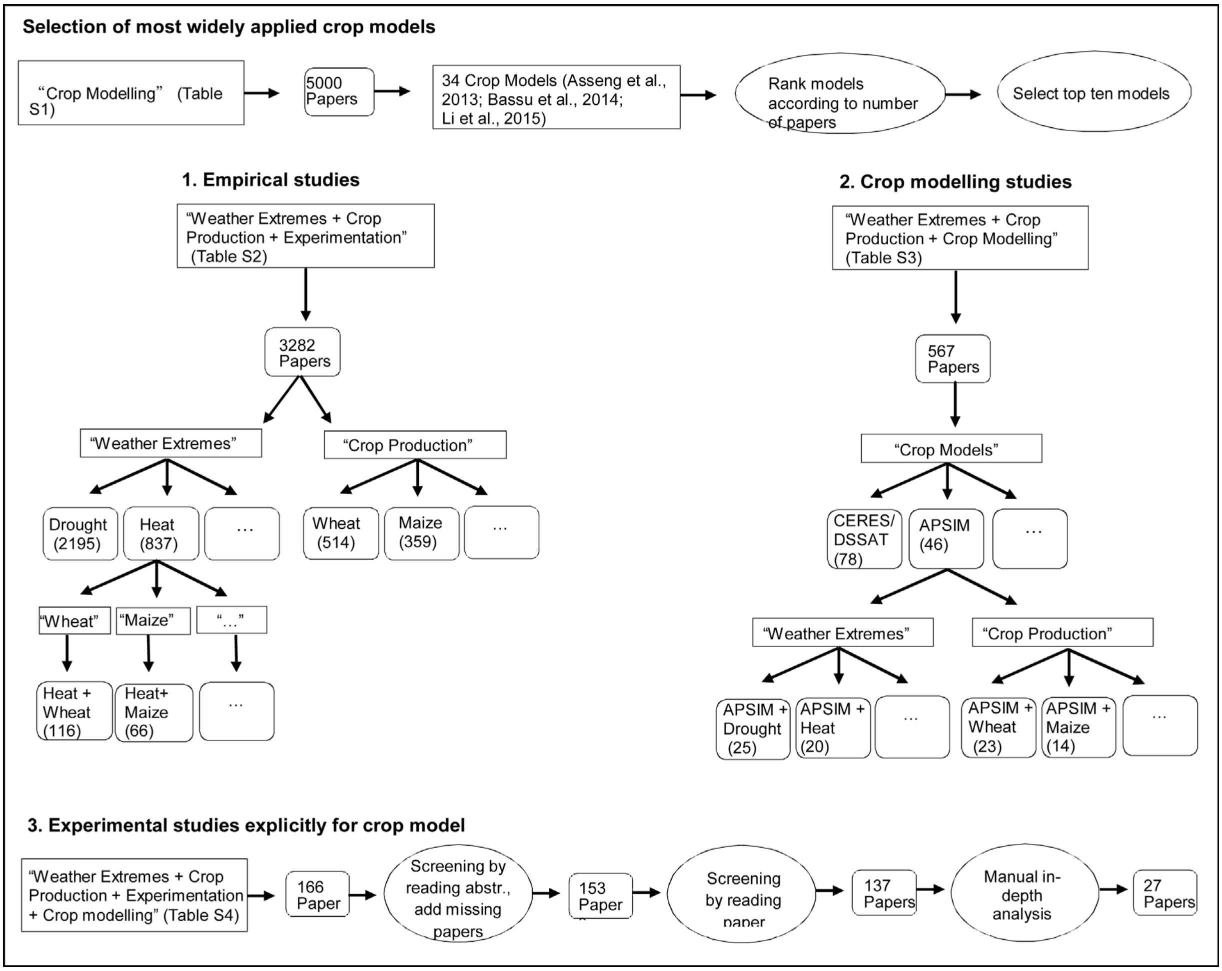

Fig. 1. Schematic of review process. In the top row of the figure, the base for the sample of crop modelling papers is presented from which then the top ten crop models were determined.

those papers with simulated impacts for the three staples wheat, maize and rice. Together, those three covered 89% of all studies.

This confirmed previous observations suggesting that empirical studies better cover the diversity of crops while modelling studies rather concentrate on the major three to five major grain crops (see, e.g. by White et al., 2011). From this we may also conclude that data sets for crops other than wheat, maize, rice may be untapped and still could be utilized to develop/enhance crop response functions to extreme weather, e.g. for crops such as sorghum, millet, soybean and groundnut (see, Section 4).

When grouping the empirical studies by the different types of agroclimatic extremes (Fig. 2a), relative to drought and heat, we found low shares of papers on heavy rain/hail/storm and on flooding. This might be partly explained by their small scale of occurrence, which makes a systematic investigation difficult.

3.2. Systematic review of crop simulation studies on impacts of key weather extremes on major crops

The second systematic search focused on identifying which models deal with specific crops and specific agroclimatic extremes and yielded 567 papers. Checking on the magnitude these same extremes were dealt with in simulation studies by the ten most widely used crop simulation models (Fig. 3b) (see, Table S5 for a documentation of those models), it turned out that 40% of the studies were carried out by representatives of the CERES/DSSAT model family, 23% by APSIM, 8% each by WOFOST and EPIC, and the remaining 21% were distributed over ORYZA2000, STICS, CROPSYST, SIRIUS, LINTUL/Simplace and HERMES.

Looking at the development of modelling studies over time, we found the share of studies by the two leading models/model families, i.e. CERES/DSSAT and APSIM, even increased markedly – with an

Table 2
No. of papers that cover specific extremes for the major grain crops.

	Wheat	Maize	Rice	Barley	Sorghum	Millet	Soybean	Ground-nut	Sum
Drought	367	251	155	91	60	26	99	52	**1101**
Heat	116	66	73	28	13	4	28	11	**339**
D*H	25	11	2	11	2	1	6	4	**62**
HR/S	40	38	57	2	16	12	15	11	**191**
Flooding	8	8	8	2	4	0	4	1	**35**
Frost	17	11	6	8	0	0	2	0	**44**
Sum	**573**	**385**	**301**	**142**	**95**	**43**	**154**	**79**	**1772**

D*H = drought and heat stress, HR/S = heavy rain/storm.

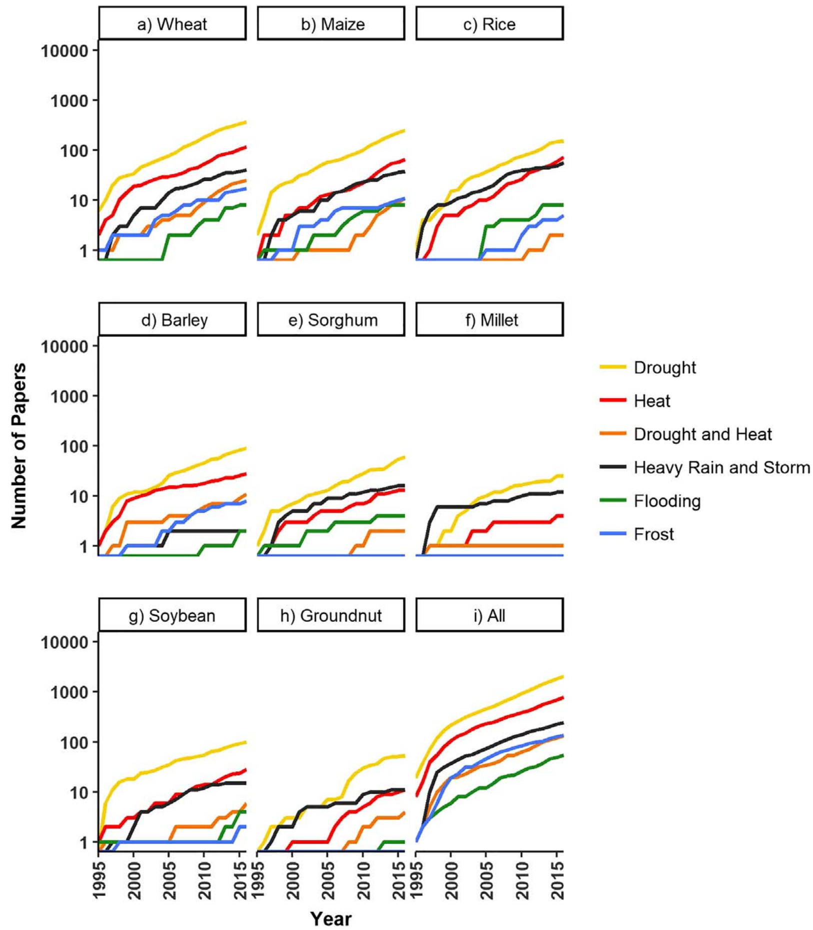

Fig. 2. Number of papers on extreme weather effects on major grain crops as observed for (a) wheat, (b) maize, (c) rice, (d) barley, (e) sorghum, (f) millet (g) soybean, (h) groundnut (i) All, that is, the sum of a to h.

especially strong increase since 2009/2010 (Fig. 4).

In Fig. 5, papers dealing with effects of the selected weather extremes on the eight crops as simulated by the ten most widely crop models are grouped by weather extreme. It showed that papers on drought followed by heat by far outnumbered papers on simulated impacts of other extremes. More than 110 papers dealt with drought and > 85 with heat. Next in line were papers on heavy rain/storm and the interaction of heat × drought (approximately 20 papers for each). There were only few modelling studies dealing with the impacts of flooding or frost – at least, for the 10 models considered here. However, several special model solutions for these processes exist, but they are not (yet) implemented in the most widely used crop models.

Fig. 5 displays a clear dominance of two crop model families (CERES-DSSAT and APSIM) that together accounted for 40–50% of all studies. Regarding studies that specifically deal with impacts of drought and of heat, those two models together accounted for more than 50% of all studies. A similar proportion was found for studies on heavy rain/storm.

When we grouped the modelling studies by the major grain crops (Fig. 6), we realized that the majority of studies were on wheat (80 papers) and maize (72 papers). On the third rank we found rice with 26 papers. Other crops were only covered by small numbers of papers. In terms of most applied models in those studies we found that again > 50% of all papers on wheat and maize were covered by CERES-DSSAT and APSIM. Noteworthy observation was that for wheat the studies conducted with APSIM had the highest share, followed by CERES-

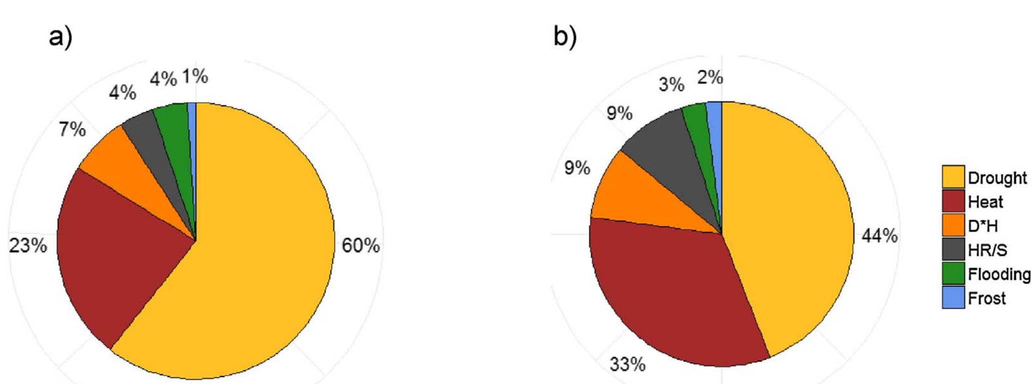

Fig. 3. Share of papers per extreme as a) observed (n = 3641) and b) simulated (n = 266).

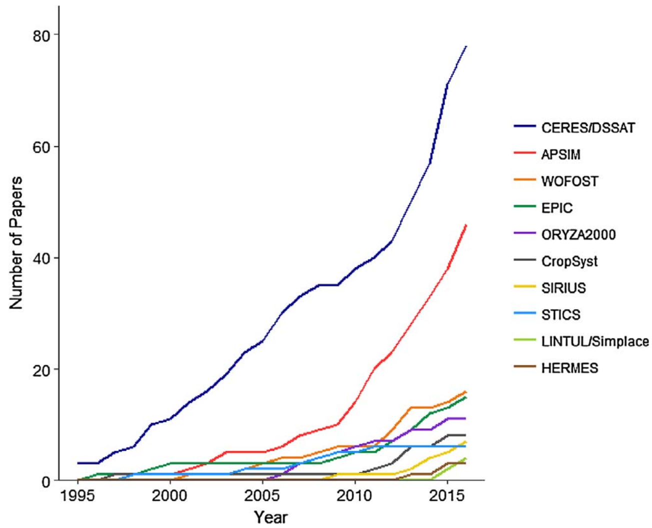

Fig. 4. Accumulated number of papers per model over time.

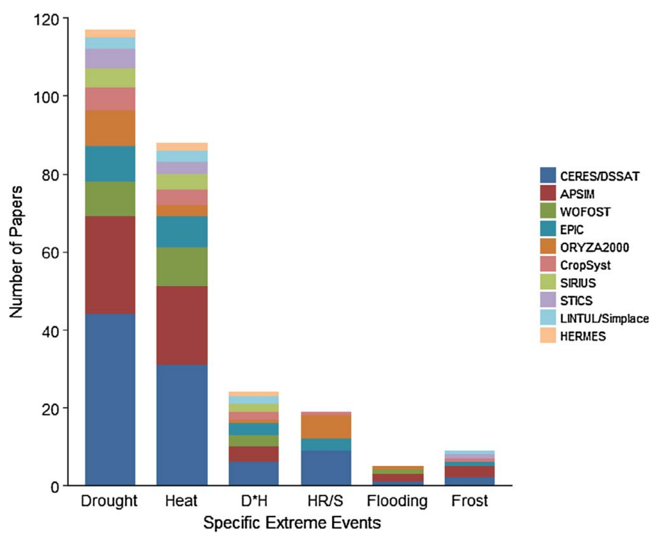

Fig. 5. Number of model specific papers (n = 262) per specific extreme event.

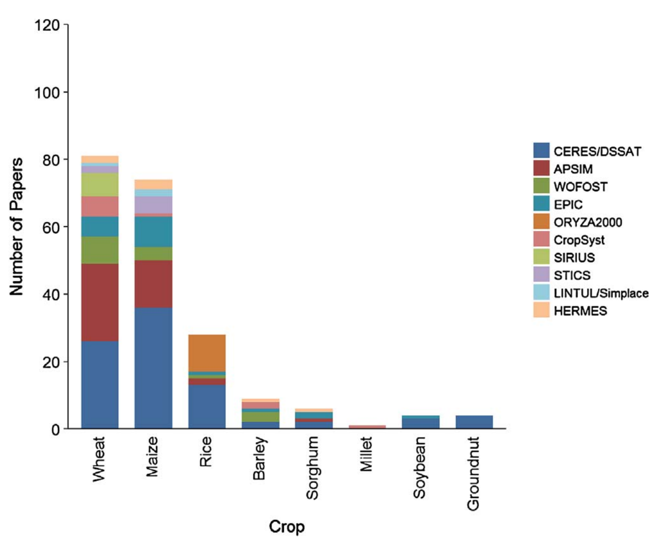

Fig. 6. Number of model specific papers (n = 207) per crop.

DSSAT, while for maize it was the other way around. This might reflect the importance of wheat for Australia (where APSIM originates from), and Maize for the US (where CERES-DSSAT originates from). For rice, a great share (> 80%) of papers were covered by models ORYZA2000 and CERES-Rice together (Fig. 5).

3.3. Systematic review of studies aimed at and found to have utilized different types of empirical data sets for model improvement

The aim of the third systematic search was to find papers that aim to use experimental data for crop model improvement, and it resulted in 166 papers. Detailed analysis of this sample showed there were some hits outside the time window or crop range (*i.e.* published before 1995, other crop than the eight selected ones); these were deleted. Concurrently, some papers obviously missing were added to the sample, which resulted in a preliminary set of 153 papers. After manual screening of these, we found that only 137 of them were indeed aimed at presenting empirical studies with the purpose of improving models to better capture crop impacts of extremes. The majority of these papers were addressed at the three globally most important staple crops maize (n = 39), rice (=21) and wheat (n = 47) – together accounting for 107 out of 137 studies. Soybean ranked fourth (n = 14), and millet fifth (n = 7). The extremes dealt with in most of the 137 studies were drought (n = 50) and heat (n = 46) (see, Table 3a).

Investigating further how many of the studies with the aim to improve models actually also led to model improvements based on the empirical data they presented, we came up with a total of 27 studies only (Table 3b). The widely applied crop models addressed most for improvement included, first, APSIM, followed by CERES-DSSAT (second) and WOFOST (third).

Again, improvement efforts for wheat and maize models were dominating, followed by models for rice and groundnut.

As shown in Table 4, just a fraction of the studies on extremes were development-stage specific. Most studies (almost entirely) concentrated on wheat, maize and rice; there were just a few on millet. Most of those studies addressed drought and heat stress during the reproductive stage (between flowering and maturity), followed by studies focusing on the flowering phases (especially for rice and maize). There were also several studies on wheat dealing with the period maturity to harvest.

3.4. Crop physiological response mechanisms and estimated yield impacts

Physiological response mechanisms for a range of adverse and extreme agroclimatic events such as heat, frost, drought, strong wind, heavy rain and flooding, have been described extensively in the literature (e.g. Barlow et al., 2015; Bodner et al., 2015; Hawkins et al., 2013; Lobell et al., 2012; Porter and Gawith, 1999; Rötter and van de Geijn, 1999; Rötter et al., 2013b,2015; Rezaei et al., 2015; Sanchez et al., 2014; Trnka et al., 2011, Gardiner et al., 2016, Sha et al., 2017). In the following we give a brief summary for main crop response mechanisms for the extremes considered in this review and a rough estimate of the yield impacts:

3.4.1. Drought

Lack of soil moisture during drought reduces transpiration rate through the reduction of stomatal conductance when crop turgor is reduced. Consequently, CO_2 flux into the intracellular space is reduced as well and limits photosynthesis resulting in lower green area for assimilation. Additionally, the reduced cooling effect of lowered transpiration will increase the temperature of the canopy leading to higher respiration of assimilates, an acceleration of crop development and shortening of the growing period especially during the establishment of storage organs. Furthermore, crop nutrient uptake is reduced. Both, timing and duration of a dry spell/period of low soil moisture determine the degree of yield penalties or crop failure (Cattivelli et al., 2008; Araus et al., 2002). For crops like wheat, maize or barley, the

Table 3a
Number of papers from selected sample that deal with empirical and simulated data aimed at model improvement and covering specific extremes for the major grain crops (n = 137).

	Wheat	Maize	Rice	Barley	Sorghum	Millet	Soybean	Groundnut	Sum
Drought	13	19	9	1	0	3	2	3	**50**
Heat	30	7	3	0	1	0	3	2	**46**
D*H	2	2	1	1	1	0	1	0	**8**
HR/S	0	0	0	0	0	0	0	0	**0**
Flooding	0	0	1	0	0	1	0	0	**2**
Frost	2	1	0	0	0	0	0	0	**3**
No extremes mentioned	0	10	7	0	0	3	8	0	**28**
Sum	**47**	**39**	**21**	**2**	**2**	**7**	**14**	**5**	**137**

D*H = drought and heat stress, HR/S = heavy rain/storm.

period around flowering has been identified to be most sensitive to drought (Rötter and van de Geijn, 1999; Rezaei et al., 2015).

3.4.2. Heat

When temperature exceeds the optimum range for a given crop, photosynthesis is reduced (Sage and Kubien 2007) and usually development rate is accelerated while respiration (Brooks and Farquhar 1985) and unproductive water loss (evaporation) increases (Larcher, 1995; Porter and Semenov 2005; Rötter and Van de Geijn, 1999), which results in reduced biomass production and yield. For cereals during reproductive stage, temperature beyond the optimum, in addition, reduces grain number and grain filling rate/grain weight, and increases leaf senescence (Porter and Gawith, 1999; Asseng et al., 2011; Rezaei et al., 2015). Grain number is largely affected by sterility and abortion of grains, which results in a non-reversible reduction in the potential yield of the crop (Spiertz, 1974, Barnabas et al., 2008). Grain size depends on the duration of grain filling, which is affected by the accelerated phenological development and senescence (Ugarte et al., 2007). Additionally, grain size is affected by cellular damage with a maximum sensitivity for heat stress, e.g. for wheat, around booting (Ugarte et al., 2007). Critical high temperature thresholds (Larcher, 1995, Wang et al., 2017a) differ by crop cultivar and vary with development stage as shown for rice (e.g. Horie et al., 1995) wheat (Wollenweber et al., 2003) and maize (Sanchez et al., 2014). Globally, the area of suitable land affected by heat stress was estimated largest for wheat (ca. 77 Mha) and rice (ca. 57 Mha) compared to maize and soybean (Teixeira et al., 2013). Asseng et al. (2015a) estimated yield loss from heat for wheat under climate change of 6% per 1 °C increase of global warming.

3.4.3. Drought × heat interactions

There are several interactions between heat and drought that can amplify yield reduction. As mentioned under 3.4.1, reduced transpiration increases canopy temperature and vapour pressure deficit will rise (Idso et al., 1981; Jagadish et al., 2011; Lobell et al., 2013; Van Oort et al., 2014;). Siebert et al. (2014) found that thermal stress time using canopy temperature was a better indicator for heat stress than air temperature. Furthermore, an increase in temperature also increases unproductive water loss through evaporation, thereby aggravating water deficits (Passioura, 1994; Lobell et al., 2013; Siebert et al., 2017a). While great advances have been made in understanding heat sterility in rice in irrigated environments (Matsui et al., 2007; Julia and Dingkuhn, 2013; Van Oort et al., 2014), the combined effect of drought and heat on rice sterility is still poorly understood.

3.4.4. Heavy rain/hail/storm

Heavy rain, hail and strong wind affect crop yield in different ways, especially depending on the development stage. Crops in the juvenile phase can be severely damaged by hail. Lodging, which is defined as "the permanent displacement of plant stems from their vertical position" (Pinthus, 1973), is a problem for many crop species throughout the world at places were plants are exposed to heavy rain and strong wind. Sha et al. (2017) provide an overview on yield reductions due to lodging, which were reported to be 31–80% in wheat, 4–65% in barley, 37–40% in oats, 5–20% in maize, and 5–84% in rice. Plants are prone to lodging at two points, the stem and the root. The stem may fail due to bending or buckling of the lower stem internodes (Neenan and Spencer-Smith, 1975), when wind pushes the stem horizontally, whereas roots may lose their contact and anchorage in soil when heavy rain decreases soil strength and increases the load which the plant must bear. Wind then acts as the force which pushes the plant over (Sterling et al., 2003). Several mechanisms were discussed to understand yield loss from lodging and stand-alone model solutions were elaborated to test hypotheses (e.g., Baker et al., 1998, Sterling et al., 2003, Berry and Spink 2012, Baker et al., 2014). For rice, mainly reduced translocation of mineral nutrients and carbon for grain filling, increased respiration, reduced carbon assimilation within the canopy, rapid chlorosis and greater susceptibility to pests and diseases are reported as main mechanisms (Hitaka, 1968). Setter et al. (1997) postulated that lodging reduces the yield of rice by self-shading and reducing canopy photosynthesis. Berry and Spink (2012) identified that yield loss for wheat can be mainly explained by inefficient radiation use by the canopy due to a reduction of leaf area that is sunlit. Additionally, lodging of cereals provides a favourable environment for leaf diseases and causes harvesting losses (Baker et al., 1998; Tripathi et al., 2003, Malik et al., 2002). Lodging also adversely affects grain quality, for example lodging inhibits grain drying due to reduced air circulation and increased humidity (Gardiner et al., 2016).

Table 3b
Number of papers from selected sample with empirical and simulated data actually dealing with model improvement regarding impacts of extremes on the major grain crops.

	Wheat	Maize	Rice	Barley	Sorghum	Millet	Soybean	Groundnut	Sum
Drought	3	7	2	0	0	0	0	2	**12**
Heat	4	2	3	0	0	0	0	0	**9**
D*H	1	1	1	1	0	0	0	0	**4**
HR/S	0	0	0	0	0	0	0	0	**0**
Flooding	0	0	0	0	0	0	0	0	**0**
Frost	1	0	0	0	0	0	0	0	**1**
Sum	**9**	**10**	**6**	**1**	**0**	**0**	**0**	**2**	**27**

D*H = drought and heat stress, HR/S = heavy rain/storm, mentioning of more than one extreme/crop per paper is possible.

Table 4
No. of papers covering specific extremes at certain development stages per crop

	Sowing – Emergence	Emergence – Start Midseason	Midseason (Start – End Anthesis)	End Midseason – Maturity	Maturity – Harvest	Unspecific
Drought			Ma**	W**, Ma***, Ri**, Mi*	W**, Mi*	W*
Heat			Ma*, Ri*	W***, Ma*, Ri*, Mi*	W***, Mi*	W*
D*H			Ma*, Ri*	W*	W*	R*
Frost			Ma*			W*
HR/S						
Flooding		Ri*				

Development stages according to ZADOK scale.
*1–5 papers, ** 5–10 papers, *** more than 10 papers.
W = wheat, Ma = maize, R = rice,B = barley, Sg = sorghum, Mi = millet, Sy = soybean, G = groundnut.
D*H = drought and heat, HR/S = heavy rain and storm.

3.4.5. Flooding/waterlogging

Excessive rainfall exceeding soil infiltration or drainage leads to water logging or even flooding. Zampieri et al. (2017) stated that water excess affects wheat production more than drought in several countries, especially in tropical regions and in some regions of the mid/high latitudes and explains yield anomalies in main wheat producing countries like China and India.

When soils are at or close to water saturation, crops suffer from oxygen deficiency (Bartholomeus et al., 2008) resulting in yield loss of agricultural crops (Dasberg and Bakker, 1970). One physiological process affected by oxygen stress at high soil moisture contents is the limitation of the metabolic activity of plants by decreased root respiration (De Willigen and Van Noordwijk, 1984).

There is evidence, that oxygen stress under the coincidence of low aeration and high temperature is more pronounced showing a higher reduction in root dry weight (Thompson and Fick, 1981) and the root growth rate (Tsukahara and Kozlowski, 1986). However, it is projected that this coincidence will occur more frequently in a future climate (Solomon et al., 2007). Also root water uptake in water logged soils is reduced (Feddes et al., 1978). Further side effects of excess water are nutrient deficiency due to leaching and detrimental effects on agronomic management, e.g. at sowing or harvest (Trnka et al., 2014). Mechanical damage is likely to occur on sloping land as a consequence of “sheet” or“gully”erosion – and in the worst case, washes away plants/parts of the crop.

3.4.6. Frost

Damage to wheat from frost has been observed in all stages of growth from seedlings through to maturity (Shroyer et al., 1995; Porter and Gawith, 1999; Fuller et al., 2007). During vegetative growth frost affects seedling survival (Fuller et al., 2007) and causes leaf damage through the destruction of cell structures (Shroyer et al., 1995). Additionally, frost without snow cover can create soil cracks leading to mechanic rupture of crop roots. However, yield impact resulting from frost damage for wheat at the reproductive stage of growth is much greater than at any other stage (Frederiks et al., 2012). Seedling death, sterility and the irreversible abortion of formed grains has by far the highest impact on cereal yield (Barlow et al., 2015). Yield losses caused by frost can be significant in some regions. Post-head-emergence frost damage to winter-habit cereals has been periodically reported for regions in Australia, Canada, and USA (Frederiks et al., 2015). Losses of 10% of wheat yield are common in parts of Australia (Fuller et al., 2007). However, the global analysis of Lesk et al. (2016) could not identify yield effects from extreme cold temperatures from national data.

3.5. Insights from in-depth analysis of studies using empirical data for model improvement and ongoing work

The bulk of the subsample of papers (n = 27) that underwent an in-depth analysis is related to the work of the agricultural systems modelling networks AgMIP (Rosenzweig et al., 2013) and MACSUR (Rötter et al., 2013a; Rötter, 2014; Ewert et al., 2015), whereby utilization of empirical data for model improvement is most advanced in the subproject AgMIP-Wheat (Asseng et al., 2013).

In the following, we exemplify the ongoing model improvement efforts by presenting major outputs from five interconnected papers documenting the scientific work (Asseng et al., 2015a; Wang et al., 2017a), as well as the associated data (Asseng et al., 2015b; Martre et al., 2017a,b).

In a major effort, to assess how anticipated increases in local temperature might affect global wheat production (see, Asseng et al., 2015a), detailed data on field experiments for wheat including year round planting and artificial heating (see, Asseng et al., 2015a,b; Martre et al., 2017a) were utilized to calibrate a large ensemble (n = 29) of wheat simulation models for estimating effects of temperature increase at 60 sites in the major wheat cultivation areas around the world and estimate global impacts (Asseng et al., 2015a). The study concluded that for each degree warming global wheat production would decrease by 6% (or by 42 Mio tons per annum) if no adaptation measures were taken. While the estimated 6% decrease per degree Celsius local temperature increase represents the mean of a large ensemble of wheat simulation models (later supported by alternative methods, see, Liu et al., 2016), a wide uncertainty range was found for yield estimates and large discrepancies in the estimates among individual models. Following up earlier work (e.g. Rötter et al., 2011; Asseng et al., 2013) suggesting that the largest share of uncertainty in yield simulations is likely to stem from modelling crop responses to temperature, Maiorano et al. (2017) followed up on this and found for a sub-set of 14 wheat models clear model improvements through re-parameterization and modification of heat stress impact on phenology, leaf growth and senescence, biomass growth, and grain number/and size using detailed field experimental data. Concurrently, Wang et al. (2017a) conducted a detailed re-assessment of the science underlying crop model algorithms describing temperature-dependent physiological processes for wheat. They hypothesized (i) that the difference among wheat models in temperature response functions is the largest source of uncertainty, and (ii) that the uncertainty in yield simulations can be reduced by improving mathematical functions describing temperature responses in wheat models. To this end, the temperature response functions from the 29 wheat models for various physiological processes (such as phenological development, dry matter increase, etc.) were analysed and assigned to (four) different response function types. Considerable variation in temperature thresholds among models below and especially beyond optimum temperatures as defined for the various processes (see, Wang et al., 2017a) were found to create considerable uncertainty; highest uncertainties were found for mathematical functions describing yield formation – and lowest for phenological development. Yet, results from a comparison of observed and simulated data of the Hot Serial Cereal (HSC) experiment (Martre et al., 2017a) indicated that improved modelling of temperature responses of phenology, photosynthesis, respiration and biomass growth is needed to reduce uncertainty in

simulating grain yield under the given temperature regimes of wheat cultivation areas. Using two crop models (APSIM and SIRIUS), Wang et al. (2017a) further investigated how much uncertainty in predicting grain yield is caused by incorporating 20 combinations of temperature response functions in those two models. It was found that > 50% of uncertainty in simulated yield is caused by using such a range of temperature response functions in the models – clearly higher than anticipated.

The way forward suggested by Wang et al. (2017a) is to further conduct model testing with the temperature response functions that they have found to be more adequate than the functions originally built in the crop models one or a couple of decades ago when less data and knowledge was available. For this further testing, Wang et al. (2017a) proposed to extend the scarce experimental data sets that allow quantification of wheat response to extremely low and high temperatures. The authors also recommended to have a closer look at how physiological processes respond to other climatic variables than temperature, as well as their interactions. They further suggest to carefully examine models on their weaknesses in response functions to temperature etc., before including them in multi-model ensembles.

In the crop modelling component (CropM) of the MACSUR project, an alternative pathway has been explored to tackle model improvements for better predicting crop impacts of extremes (see, Rötter et al., 2013a). That may be due to the experience of researchers regarding a particular discrepancy between yield predictions and observations in central Europe: in years with high rainfall and cool summers, crop simulations produced highest yield estimates while in reality wheat yield in the drier and hotter years were higher (Olesen et al., 2011). One explanation for that discrepancy has been that crop simulation models may well be adequately sensitive to drought yet not sufficiently sensitive to other abiotic stresses such as frost, heavy rains or flooding associated with cool and wet years. Conditions that usually promote plant growth, such as abundant soil nutrition and moisture leading to high ear weights are also increasing the risk for lodging (Vera et al., 2012). Based on earlier broad characterization of shifts in agroclimatic conditions in Europe under expected climate change (Trnka et al., 2011), combined with thorough literature study for wheat, a set of 11 agroclimatic indicators was defined to represent the most important adverse and extreme agroclimatic events for wheat in Europe. For 14 representative sites across Europe, it was then examined how the probability of single and multiple stresses for wheat would be altered under anticipated climate change (Trnka et al., 2014). One of the conclusions of that study was that especially the expected higher frequency of multiple adverse events would be detrimental/causing severe yield penalties. This study gave rise to start experimental work to investigate in detail the effects of interactions between extreme heat and drought on wheat yield. First results for a number for contrasting wheat cultivars indicate that the cultivar response patterns are quite diverse (Hlavacova et al., 2017, Urban et al., 2018), and so will then consequently be the response functions for phenology, photosynthesis, biomass growth and yield formation.

4. Discussion

4.1. Outcome from the systematic reviews

4.1.1. Empirical data to increase quantitative understanding

The concentration on just a few weather extremes and major crops has increased over time. Moreover, there has been an enormous increase in the number of studies on agroclimatic extremes since start of the review period in 1995.

Studies on drought have shown predominance over other extremes. This has been the case right from the start of the review period; for some crops, such as wheat, barley or millet, that predominance even increased over time. This can be explained by the fact that the increased demand and competition for water among various sectors has led to the fact that growth in agricultural water demand has exceeded that in supply. In some important agricultural regions, water supply has actually declined (see, Dai, 2013; Trenberth et al., 2015; Lesk et al., 2016; Frieler et al., 2017; Wang et al., 2017b).

There is still relatively little work on crop impacts of multiple agroclimatic extremes (see, also Mittler, 2006; Rossini et al., 2016). Our review indicates that only after around 2010 some more studies pay attention to the interactions of heat and drought.

An explanation for the enormous increase in number of studies might be found in two major changes in the societal awareness of the importance of crop impacts of extremes – both occurring more or less simultaneously (around 2007/2008): (i) on the importance and severity of climatic change with more frequent extremes for mankind at large – and for agriculture in particular (Kalkuhl et al., 2016; Wossen et al., 2017) – and (ii) on the importance of investments in agricultural research – triggered by the food price crises in 2006/07 – to overcome complacencies with respect to food security (Von Braun, 2008).

The increasing awareness of the severity of climate change impacts came with the 4th Assessment Report (AR4) of Intergovernmental Panel on Climate Change (IPCC, 2007) with its clear scientific messages, and their "translation" for policy makers and the broader public by a policy maker (Al Gore) – for which both, Al Gore and the IPCC were awarded the Nobel Peace Prize in 2007. This has been a crucial stepping stone for revitalizing the interest in and stimulating many climate impact scientists (experimenters and modellers) to increase their research efforts on climate impacts, adaptation and mitigation strategies for the various sectors. While till recently the renewed efforts were in the first place devoted to crop modelling studies (see, Porter et al., 2014), too little effort has been devoted yet to conduct targeted experiments to generate new data as needed for closing knowledge gaps on the impacts of agroclimatic extremes and their interactions for a broad range of agricultural crops (as postulated earlier, by e.g. Rötter et al., 2011). Such data would be urgently required to enable better adaptation planning and support for achieving the Sustainable Development Goals (SDGs)– especially those on poverty, hunger and nutrition/good health (SDGs 1,2 and 3) (http://www.un.org/sustainabledevelopment/).

4.1.2. Inventory of available process-based crop modelling studies and approaches to capture extremes

With respect to relevant modelling studies CERES-DSSAT, APSIM and OYZA2000 are clearly dominating. Out of the ten most widely applied crop simulation models considered here, two models are crop-specific (i.e. ORYZA2000 for rice, and SIRIUS for wheat), while the others are generic models – that means they cover a wide range of different crops/cropping systems (see, also Table S5).

Between 2007 and 2010 awareness among crop modellers has been growing of the need to detect crop model deficiencies, in particular with respect to the impacts of agroclimatic extremes such as heat and severe water deficits during critical growth stages. In a first phase, modelling groups gathered to conduct comparisons of the performance of widely used crop models under current climatic conditions (means and variability) at multiple locations – namely, the studies conducted on wheat, barley and maize in Europe under COST action 734 (Palosuo et al., 2011; Rötter et al., 2012, Eitzinger et al., 2013; Salo et al., 2016). Subsequently the AgMIP project invited a much larger number of crop models, especially for wheat (Asseng et al., 2013, 2015a), maize (Bassu et al., 2014) and rice (Li et al., 2015) for being compared under current and projected future climate. A direct output of those model inter-comparisons for wheat has been that improvement of temperature response functions is crucial to reduce uncertainties in the quantitative estimates of climate change impact on wheat production (Asseng et al., 2013; Wang et al., 2017a; Maiorano et al., 2017).

The inter-comparison of 21 crop models applied on experimental data for maize in a Free Air CO_2 Enrichment (FACE) experiment (Manderscheid et al., 2014) revealed that models captured only 30% of the beneficial effect of elevated CO_2 concentration on yield during

drought periods and highlighted the necessity to improve maize models with respect to simulate the CO_2 effect on transpiration and its impact on water status during the kernel-set phase (Durand et al., 2017).

A feature that sporadically has received the specific attention of crop modellers has been the impact of (short periods) of extremely high temperature during the flowering phase and the grain filling period of cereals (Wheeler et al., 2000; Rezaei et al., 2015) – in particular for wheat (Asseng et al., 2011), rice (Horie et al., 1995) and maize (Lobell et al., 2013) – but also for other crops like groundnut (Challinor et al., 2005) or sunflower (Moriondo et al., 2011).

Modelling approaches applied to describe this heat stress effect are quite similar following the approach by Wheeler et al. (2000) and Challinor et al. (2005), relating the reduction in total grain set to (crop-specific) temperature thresholds through modifying/reducing the daily increase in harvest index (HI) relative to non-stressed conditions. Similar approaches have been operationalized in various models, such as in CROPSYST for sunflower (Moriondo et al., 2011) or in MONICA for barley (Nendel et al., 2011).

Another feature receiving some attention has been heat stress during the grain filling period with leaf senescence, e.g. for wheat, accelerating as a result of temperatures $> 34\,^{\circ}C$ (Asseng et al., 2011).

4.1.3. Studies identified that aim to demonstrate model improvements

As mentioned above, only recently we find more targeted (and partly concerted) efforts to exploit or generate empirical data for crop model improvement to better capture impacts of extremes. This happens with a considerable time lag – linking up with a few dedicated early efforts – such as for modelling heat stress impact on rice at flowering (Horie et al., 1995).

We found a limited number of good recent examples (see, Table S6). Apart from those related to AgMIP-wheat there were also a couple of other studies, such as for maize (e.g. Gabaldón-Leal et al., 2016) and rice (e.g. Van Oort et al., 2014).

The study of Van Oort et al. (2014) illustrated how new experimental data collected over a couple of years on a number of processes have been implemented, and finally resulted in a clear improvement of crop model ORYZA2000 – which had failed to reproduce rice yield under extreme temperature conditions. Model modifications derived from the new data were: (i) improved description of phenological development replacing temperature thresholds/cardinal temperatures for different phenological stages and leaf growth (ii) better description of spikelet formation, and (iii) improved description of heat- and cold-induced spikelet sterility during flowering. The latter implied that transpirational cooling of the canopy (see, Webber et al., 2017) as well as the feature of adaptive early morning flowering (see, also Bheemanahalli et al., 2017) was taken into account for improving the respective mathematical functions for spikelet sterility.

The implementation of canopy temperature instead of air temperature as a driver has recently also been tested for nine wheat models (Webber et al., 2017). Aim of the study was to examine whether simulation of crop canopy temperature (T_c) would improve the capability of crop models to simulate heat stress impacts on irrigated wheat systems. The models were tested in a semi-arid environment and compared with their counterparts driven by air temperature (T_{air}) recorded at 2 m (Stevenson Screen) height. The models used different approaches for generating T_c – not all of them satisfactorily. Under the given conditions the use of T_c to account for heat stress effects did improve wheat yield simulations significantly only for 2 out of 8 models compared to using only T_{air}, while improvement for the others was less pronounced. One reason was that simulation of T_c especially using energy balance approaches with neutral stability showed a poor performance and could not reflect the observed magnitude of the "transpirational cooling" resulting in only small simulated differences between T_{air} and T_c. The authors stated that their results needed to be validated across a wider range of climates and growing conditions including rainfed production.

4.2. Limitations of the study

We restricted our systematic literature searches to SCOPUS database, and considered only journal papers published in four languages (English, French, Spanish, German). Based on the high number of hits, we do not think that inclusion of more databases would have had increased the output considerably – yet that would have to be verified. Not including Russian or Chinese may have led to missing quite a number of empirical studies on agroclimatic extremes but probably did not considerably reduce the number of relevant modelling studies.

There was possibly some small bias introduced by using those crop models put to the test by the AgMIP network for the main staples (wheat, maize, rice) as a filter for selecting the top ten crop models further considered. Yet, also earlier reviews and model inter-comparisons (see, White et al., 2011; Kersebaum et al., 2007) ended up with a similar ranking.

In this review we consciously left out empirical statistical modelling of the impacts of agroclimatic extremes while these would have been potentially valuable – especially for such extremes (such as flooding/excess water) for which there are currently no appropriate mathematical functions that could be incorporated in process-based models (see, Trnka et al., 2011, 2014; Rötter et al., 2013b; Zampieri et al., 2017). Yet, in order to make progress in this respect we propose to include statistical models and compare their outputs to those of process-based models. Lessons from comparing both approaches and possibly combining them might lead to better quantification (see, Section 4.4).

4.3. Assessing short-comings of current work

We already discussed that the outcomes of our systematic reviews showed knowledge gaps that need to be filled by more experiments on the crop impacts of neglected/under-researched extremes such as flooding and heavy rains/hail and storms, and a range of crops/cropping systems likely to be exposed to more frequent and severe extremes.

A question that arises is what kind of experimentation is needed and should receive priority for reducing the main crop model deficiencies regarding agroclimatic extremes?

We will not treat here the pitfalls and technical short-comings of current experimental set-ups of assessing crop impacts of extremes (see, e.g., Rezaei et al., 2018), but rather direct the attention to challenges that have received too little attention in relation to their potential damage – such as assessing multiple stress impacts on crops (in models and experiments).

Multiple stress impacts are not equal to adding up impacts of individual stresses (see, Boyer, 1982; Barnabas et al., 2008; Mittler, 2006; Rossini et al., 2016). Mittler (2006) has shown this for heat × drought interactions. This observation has been confirmed by recent research on wheat genotypes (e.g. by Hlavacova et al., 2017, Hlaváčová et al., 2018), also highlighting how different the response patterns of different genotypes can be – as shown elsewhere in depth for crop response patterns to drought (Moshelion et al., 2014). One more example for the effect of multiple abiotic stresses presented here is associated with heavy rainfall, causing deep percolation and resulting in very high nitrate leaching rates. While the latter do not directly affect water-limited yield, most farmers would probably not fertilise directly afterwards, possibly resulting in nitrogen deficiency.

Another aspect we want to highlight with respect to multiple stresses is that abiotic stress(es) can be, and often are, linked to biotic stress(es) – for example, drought being inductive for aflatoxin infection in peanut, or excess water for *phoma* in oilseed rape. In many cases it has been found that an abiotic adverse event is not the main cause of yield penalties but it causes an ideal environment for the development of biotic stresses.

An additional point that deserves to be examined is how many studies do analyse a crop's below ground responses to various agroclimatic extremes? More provocatively, we could ask whether studies are

useful that just look at aboveground processes in response to extreme events?

While putting forward these questions, we are fully aware that in crop modelling a reasonable balance between simplification and complexity must be maintained not to defeat the purpose of models that are supposed to be applicable for a wide range of environments (e.g. Rötter et al., 2011; Van Oort et al., 2014).

4.4. Perspectives for future collaborative work

Process-based crop models have proven to be key tools for understanding the processes of the complex interconnections in cropping systems, and for assessing climate impacts and adaptation options for crop systems (e.g. Porter and Semenov, 2005; Kahiluoto et al., 2014; Chenu et al., 2017). However, they are not yet fully fit for adequately capturing crop impacts of extremes. To further progress, we suggest two pathways:

The first pathway recognizes that there are different approaches to quantify crop impacts of agroclimatic extremes that could complement and support each other. An example of how deficiencies in the quantification of impacts of extremes can be detected and possibly help to improve models by confronting results from using two different approaches has been given by Siebert et al. (2017a): global analyses on yield anomalies in wheat and maize were carried out using (i) an ensemble of gridded process-based crop models (Frieler et al., 2017) and (ii) empiricial statistical models with due attention to various agroclimatic extremes (Zampieri et al., 2017). The two studies came up with different conclusions. The study by Frieler et al. identified water deficits as the major factor determining yield anomalies, while Zampieri et al. found that in most cases heat stress is the most influencing factor (see, also Matiu et al., 2017). Hence, results of the two approaches deviate, and it would then be worthwhile to investigate in which regions/climatic zones results agree or disagree.

We anticipate that still for quite some time (next 10–20 years) experimentation and empirical databases still need to be expanded to enable improvement of process-based models to such an extent that they adequately capture the impacts of the major agroclimatic extremes and their combinations and deliver robust and accurate estimates on yield penalties.

For the mean-time, we suggest systematic comparison and exchange among empirical statistical and process-based modellers (see, e.g.; Lobell and Asseng, 2017; Rötter et al., 2013b; Siebert et al., 2017a) for the mutual benefit of improving and combining their approaches.

The second, forward-looking pathway, deserving a special subsection – as a synthesis of our review – is elaborated below.

4.5. No modelling without experimentation and no experimentation without modelling

Finally, we suggest to extend the leitmotiv of C.T de Wit "No modelling without experimentation" by "and no experimentation without modelling" (according to S. Asseng, pers. Comm.), i.e. crop production systems are complex, and so, the response of such systems towards agroclimatic extremes. For instance, when we observe yield reductions in seasons with low rainfall or excessive rainfall, these can be caused directly by water deficiency or oxygen stress, respectively. However, as stated above there might be more yield reduction factors which are linked to the climatic extreme, like nitrogen leaching, pest and disease incidence. Or, as discussed above, they can be interconnected- such as often heat and drought, which are interacting with the current state of the canopy development, etc. This underlines the importance of applying a systems approach when investigating impacts of agroclimatic extremes. Experiments, greenhouse as well as field trials, are always limited to few treatments (for instance, different levels of water supply; including now also nitrogen or even pests would dramatically increase the number of trial plots), and only few variables will be measured (for instance, only very few experiments will measure nitrogen leaching, only when there are very good reasons for it). This bears the risk that indirect/direct reasons which are not obvious (or considered as it) will be neglected. Therefore, a sound calibration of a model requires a balanced data set, which includes observed state and flux variables representing as many of the processes and states of the model as possible at temporal (and spatial) resolutions that allow process parameters in the model to be adjusted and model assumptions to be tested (Kersebaum et al., 2015). At the same time, as discussed above, crop models are by far not at the stage to cover all yield limiting factors, and need improvement. Taking this into account, we envisage the following iterative, linked model development and experimentation cycle:

1. Real world observation/problem identification regarding negative crop impacts – as a starting point
2. Model run under different conditions (multi-location and multi-annual) – does it reproduce the effect on yield? Discussion of various model outputs with experts
3. Are the model outputs in line with model expert opinion? Very interesting will be to investigate surprising results
4. Then specific targeted experimentation (greenhouse and/or field experiments) for eliminating likely model deficiencies or to unravel the causes for the surprising results of the model
5. Model modification based on newly generated empirical data
6. Model validation/check on model improvement with performance statistics
7. Larger scale model simulation – and comparison of output against real world data at higher aggregation levels, quantification of yield loss
8. Adaptation scenario using a model sensitivity analysis for Genotype by Management (G × M) for a given Environment (E)
9. Targeted experiments using G × M as suggested for the model against G × M status quo
10. Attend to remaining/new problem(s) and start new cycle (to target better/more effective experimentation).

5. Conclusions

Despite much recent research and advancements made in terms of modelling agricultural impacts of and adaptations to climate change, the success in true crop model improvements and generation of new data to more adequately capture impacts of agroclimatic extremes is still limited. Likewise, there has been little change in terms of the focal crops, farming systems and regions agricultural research is invested in. The latter requires massive re-direction of research towards crops/farming systems most vulnerable and likely exposed to more severe agroclimatic extremes such as in many tropical regions. The previous require concerted international efforts and coordination (see, Rötter, 2014) by the agricultural research and policy communities similar to the efforts undertaken by the Intergovernmental Panel on Climate Change (IPCC) with the climate and earth systems science & policy communities.

Results of this review give rise to a number of recommendations (listed below) that refer to improvement of models and associated experimentation – as well as on better linkages between experimentation and model improvement:

- Experimentation needs to be more targeted at certain types of drought (early season, mid season or terminal drought)
- Much more experiments than conducted currently are required to systematically examine interactions of multiple stresses (such as heat × drought; drought × heavy rain; heavy rain × storm/hail × flooding). Such multiple stress combinations appear to be most detrimental to crop production (Barnabas et al., 2008; Mittler, 2006; Moshelion et al., 2014; Pagani et al., 2017; Zampieri et al.,

2017).

- To fill obvious knowledge gaps, more experiments need to be conducted on crop impacts of neglected/under-researched crops and crop rotations (Kollas et al., 2015), as well as on under-researched extremes such as flooding and heavy rains/hail and storms.
- Field experiments that were affected by extreme events with severe crop failure are often terminated without the estimation of damages and crop yield losses. These data are required to test newly implemented algorithms to consider the impact of extremes in crop models.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2018.02.023.

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